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| 13. ABSTRACT (Maximum 200 words)<br>We proposed to complete three tasks in this project. These tasks were MRFM imaging with nanometer-scale resolution, end-to-end performance analysis of quantum spin imaging, and a reference design for a year-2006 quantum microscope. At the time of this report, nanometer-scale MRFM imaging has been achieved at 80nm resolution. A performance analysis was completed, and published as an invited paper in the Proceedings of the IEEE on the Classical and Quantum Theory of Thermal Magnetic Noise. With recent work in spin simulation exactly matching recent experiments performed at IBM, this technical report represents the deliverable of a complete Reference Design and Performance Analysis (RDPA) as originally proposed. |   |  |   |  |
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Enclosure 1

We proposed to complete three tasks in this project. These tasks were MRFM imaging with nanometer-scale resolution, end-to-end performance analysis of quantum spin imaging, and a reference design for a year-2006 quantum microscope. At the time of this report, nanometer-scale MRFM imaging has been achieved at 80nm resolution. A performance analysis was completed, and published as an invited paper in the Proceedings of the IEEE on the Classical and Quantum Theory of Thermal Magnetic Noise. With recent work in spin simulation exactly matching recent experiments performed at IBM, this technical report represents the deliverable of a complete Reference Design and Performance Analysis (RDPA) as originally proposed.

We cautioned, in the original proposal, that small university groups like ours can only reasonably expect to optimize at most two or three of the ten modular subsystems: magnetic tip, cantilever, interferometer, control, spin modulation, sample positioning, signal multiplexing, imaging algorithms, vacuum, and cryogenics. Nevertheless, in this complex collection, we have significantly advanced on the Signal-to-Noise (SNR) metric as originally proposed. In particular, as previous progress reports have stated, contributions have been made in sample positioning, tip and cantilever fabrication, interferometry, and imaging algorithms.

We completed tasks for year one with the calibration of a 3D MRFM scanner, testing three imaging techniques, and deconvoluting a raw image force map of spin density and the MRFM point spread function. Our results included 80nm voxel resolution, with a reconstructed image that correctly identified the location and orientation of the surface, and mapped the spin distribution within the solid. These results were published in the Review of Scientific Instruments:

Shih-hui Chao, William M. Dougherty, Joseph L. Garbini, and John A. Sidles, Nanometer-Scale Magnetic Resonance Imaging, REVIEW OF SCIENTIFIC INSTRUMENTS, VOLUME 75, NUMBER 5, MAY 2004.

Dr. Shih-hui Chao received his PhD in our MRFM program on this work, graduating 2002 with a thesis publication entitled, “3D Imaging by Magnetic Resonance Force Microscopy, UNIVERSITY OF WASHINGTON PRESS, 2004.” His thesis detailed the technical challenges and accomplishments for our 2004 article.

Integrating the subsystems to achieve these results is an engineering feat, and suggests that developing this technology will depend on a programmatic investment to fully implement all ten subsystems in working instruments. In support of this end, in year two, consistent with our proposal, we pursued the performance analysis of decoherence mechanisms in thermal magnetic noise that are

ubiquitous in these types of spintronic devices.

The performance analysis of our device encouraged us to also pursue design improvements for our 3D scanner as well as test improved tip and cantilever systems. We sought, and obtained approval, to buy subcontract services from the University of Nebraska for ion-beam milling of tips and cantilevers under the direction of Sy-Hwang Liou. Dr. Liou's final technical report is attached.

In addition, we concentrated on sample preparation techniques to further refine our imaging results. Our analysis continued to benefit from experiments as evidenced by a graduate student project on hysteresis and creep.

Curt J. Salisbury, Control of a Piezoelectric Sample Scanner for MRFM, Thesis, UNIVERSITY OF WASHINGTON PRESS, 2003.

The performance analysis task in the original proposal was combined in the milestone II with a reference design as a complete package for an RDPA. We discovered in year two that integrating the tips and cantilevers from Nebraska, as well as comparing our samples in SEM and TEM, required more time, and we took a 12-month, no-cost extension under institutional authority. At this transition, a DARPA program was underway to make the kind of programmatic investment necessary for turning these devices into instruments. We employed a software engineer on a separate project as part of the DARPA MOSAIC program, and redoubled our efforts for an RDPA as the deliverable on this Accelerated Development of MRFM project. In the Fall of 2003, we published our theoretical results as part of an invited paper for the IEEE.

John A. Sidles, Joseph L. Garbini, William M. Dougherty, and Shih-hui Chao, The Classical and Quantum Theory of Thermal Magnetic Noise, with Applications in Spintronics and Quantum Microscopy, PROCEEDINGS OF THE IEEE, VOL. 91, NO. 5, MAY 2003.

In continued pursuit of experimental verification, we decided to integrate all three tasks in the final year to include the improved 3D scanner and an interferometry tracking scheme for control of 10nm steps over  $1^3\mu m$ . In addition, we lowered our cryostat operation from 80K to 10K. Improvements in software, computing power, and fabrication techniques all supported these system changes. Performance analysis proceeded in-step, and a reference design emerged to include complete end-to-end simulation and a 3D bio-image.

The E2E simulation embodies the following physical model:

- cantilever dynamics that are fully quantum-mechanical

- measurement dynamics that are fully quantum-mechanical
- backaction dynamics that are fully quantum-mechanical
- closed-loop control that is fully quantum-mechanical
- thermal noise that is fully quantum-mechanical, including cantilever excitation and damping, and thermal spin decoherence
- spin dynamics that are fully quantum-mechanical, as mediated by the magnetic gradient of the cantilever tip
- dipole-dipole interactions among the spin

On our education front, a course in spin mechanics was implemented, and several “spinometers” were produced in simulation as a result. High-school student, Chris Mounce, published his on our website:

<http://courses.washington.edu/goodall/MRFM/>

The foundations for the RDPA were laid on these ideas:

1. All uniaxial spinometers collapse to eigenstates
2. All triaxial spinometers collapse to coherent states
3. All biaxial controlled spinometers collapse to thermal states

These quantum limits are universal and, hence, found to be applicable in experiments at LIGO. In this larger effort, our simulation theory was put to the test at LIGO with their more demanding specifications for control in the application of interferometry measurements. Following presentations for the developing RDPA, the MRFM group at the University of Washington was invited to join the LIGO Scientific Collaboration (LSC). John Sidles subsequently collaborated with Daniel Sigg at LIGO on a publication examining these quantum limits in such devices:

John A. Sidles, Daniel Sigg, Optical Torques in Suspended Fabry-Perot Interferometers, LIGO-P030055-B, submitted to PHYSICAL LETTERS A, 2004.

In addition, the Principal Investigator developed a closed form for a positive P-representation of the spin- $j$  thermal density matrix. The formalism that can be applied to magnetic resonance force microscopy (MRFM) and gravity wave (GW) interferometry was published on the pre-print server:

John A. Sidles, Positive P-Representations of the Thermal Operator from Quantum Control Theory, quant-ph/0401165.

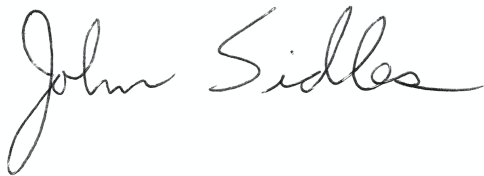
Although the Accelerated Development of MRFM project funded by the ARO ended June 2004 with the tasks completed and the milestones accomplished, we have continued testing the 3D scanner and proven the interferometry tracking. A graduate student on a separate project provided software and optics with a feed-forward pulse shaping technique that reduces cantilever damping time and allows faster, more controlled, movement of the tip over a sample. A graduate student on a separate project provided samples with paramagnetic properties in 200nm spheres doped with DPPH that we will use to prove 3D, non-destructive, bio-imaging.

As a final contribution to the RDPA, the PI developed a series of simulations to prove the Random Telegraph Signal (RTS) assumption of the most important MRFM results to date - the experiments at IBM that were published in Nature July 2004. These simulations completely match experiment, and indicates that all single-qubit readout devices will observe spin polarization as a unit-magnitude random telegraph signal (RTS) embedded in white noise. This principle holds independently of: (1) whether the SNR is low or high, (2) the details of the detector design, and (3) the physical origins of the spin decoherence.

Advances are in-hand with quantitative agreement among performance analysis, experimental imaging data, and numerical simulations. These results illustrate the success of this project for the Accelerated Development of MRFM.

Thank you very much, and we look forward to achieving single-spin quantum microscopy by the Year 2006 as originally proposed.

Sincerely,



John A. Sidles, PhD  
Professor  
Department of Orthopaedics  
School of Medicine

## 6. Listing of publications and technical reports:

### (a) Papers published in peer reviewed journals:

Shih-hui Chao, William M. Dougherty, Joseph L. Garbini, and John A. Sidles, Nanometer-Scale Magnetic Resonance Imaging, REVIEW OF SCIENTIFIC INSTRUMENTS, VOLUME 75, NUMBER 5, MAY 2004.

John A. Sidles, Joseph L. Garbini, William M. Dougherty, and Shih-hui Chao, The Classical and Quantum Theory of Thermal Magnetic Noise, with Applications in Spintronics and Quantum Microscopy, PROCEEDINGS OF THE IEEE, VOL. 91, NO. 5, MAY 2003.

Sidles, J.A., Sigg, D., Optical Torques in Suspended Fabry-Perot Interferometers, LIGO-P030055-B, 2004

### (b) Papers published in conference proceedings or non-peer reviewed journals:

Curt J. Salisbury, Control of a Piezoelectric Sample Scanner for MRFM, Master's Thesis, UNIVERSITY OF WASHINGTON PRESS, 2003.

Matthew N. Church, Dual Wavelength Interferometry for Sample Position Control in Magnetic Resonance Force Microscopy, UNIVERSITY OF WASHINGTON PRESS, 2003.

Chao, Shih-hui, 3D Imaging by Magnetic Resonance Force Microscopy, Doctoral Thesis, University of Washington Press, 2004.

Sidles, J.A., 3D Quantum Biomicroscopy: We Must See, We Will See, in session, "Quantum Technology Is Here: Where Will It Take Us and When?" American Association for the Advancement of Science (AAAS) Meeting, Seattle, WA, February 14, 2004

Sidles, J.A., Efficient Quantum Algorithms for End-to-End MRFM Analysis, American Physical Society (APS) Meeting, Montreal, Quebec, CANADA, March 26, 2004

### (c) Papers presented at meetings (oral or posters), but not published:

Sidles, J.A., Efficient Quantum Algorithms for End-to-End MRFM Analysis, Caltech Chemistry Symposium, Caltech, CA, April 12, 2004

Sidles, J.A., What if We Could See Molecules? Science Fiction Writers Association Annual Meeting, Seattle, WA, April 16, 2004

(d) Manuscripts submitted, but not published:

Sidles, J.A., Positive P-Representations of the Thermal Operator from Quantum Control Theory, quant-ph/0401165

(e) Technical reports submitted to ARO:

- Interim progress report, 07/01/01 - 06/30/02
- Interim progress report, 07/01/02 - 06/30/03
- Interim progress report, 07/01/03 - 12/31/03
- Final technical report, 07/01/01 - 06/30/04

7. Participating personnel and degrees:

- John A. Sidles, PhD, PI
- Joseph L. Garbini, PhD, Co-investigator
- William M. Dougherty, PhD, Co-investigator
- Shih-hui J. Chao, PhD, Grad Student, PhD earned on this project
- Curt J. Salisbury, MS, Grad Student, MS earned on this project
- Matthew N. Church, Grad Student, MS
- R. Douglas Mounce, MS, Manager
- Sy-Hwang Liou, PhD, Co-investigator

*Subcontract Title:*

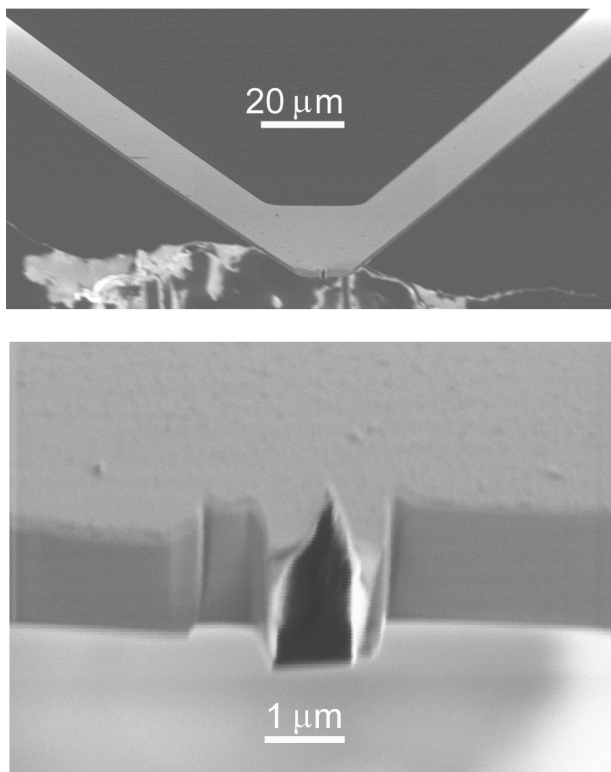
**Scanning Probes for Magnetic Resonance Force Microscopy**

Sy-Hwang Liou  
University of Nebraska

**Report:**

We have fabricated advanced tips with a well-defined particle size and controlled tip magnetic properties. Fig. 1 shows a focused ion beam milled cantilever with about nanometer-size CoSm permanent magnetic particles on the tip that was sent to Professor John Sidles at the University of Washington. The smaller size and elongated shape of the magnetic particle result in much improved the spatial resolution and magnetic field gradient from the tip.

These tip are estimated with a field gradient of 1G/nm



**Fig. 1 Small SmCo5 permanent magnet for high magnetic force gradient**

Cantilever with a small SmCo5 permanent magnet

Bottom Fig. is a enlarged view of the cantilever with a small SmCo5 permanent magnet